1. **PI and Co-I Names and Affiliations**:

Principal Investigator:	Henry E. Revercomb, Space Science and Engineering Center, University of Wisconsin-Madison
Co-investigators:	Robert O. Knuteson, David C. Tobin, Von P. Walden, Space Science and Engineering Center, University of Wisconsin-Madison
Co-investigator:	David D. Turner, Pacific Northwest National Laboratory

2. **Title of Research Grant**:

High Spectral Resolution FTIR Observations for the ARM Program: Clear and Cloudy Sky Applications, (DE-FG-02-90ER61057)

3. **Scientific Goal(s) of Research Grant:**

ARM data sets now include accurately calibrated spectra of downwelling infrared radiance from five locations at the Southern Great Plains site, from two locations in the Arctic and from Nauru island in the Tropical Western Pacific. These observations are produced by the Atmospheric Emitted Radiance Interferometer (AERI) systems developed under this grant and are used by many ARM Science teams. We have used the extensive observations from AERI and a wide range of other ARM instruments to help address important clear sky issues in cooperation with the Instantaneous Radiative Flux working group. Scientific goals of this research grant are to bring closure to several clear-sky atmospheric state and longwave radiative transfer issues of our current work, as well as to follow logical extensions into new areas. One significant new emphasis is the use of AERI radiances and retrievals for cloud model performance testing. Observed time averages and statistical properties of cloud radiative forcing and the effect of clouds on the atmospheric state and their comparison to output from Single-Column, Cloud-Mesoscale, and global numerical weather prediction models is being studied. Also, recent forward model findings are being used to improve remote sensing of atmospheric temperature and water vapor from the AERI observations. A final goal is to continue our strong involvement in the ARM Water Vapor measurements with a focus on reaching closure on the absolute accuracy of ground based integrated column water vapor measurements and the use of Raman lidar as a key tool for the upper troposphere.

4. **Accomplishments:**

- Organization and planning of WVIOP 2000 and AFWEX, upcoming IOPs aimed at improving and quantifying our ability to measure atmospheric water vapor. Scientific and logistical information regarding the experiments is available at http://yard.arm.gov/~turner/afwex/.

- Derivation of refined self-broadened water vapor continuum coefficients and their uncertainties in the 8 to 12µm spectral region based on an analysis of the SGP site AERI/LBLRTM QME data set. Using the existing MWR water vapor values, we find the coefficients need to be decreased by 5%-10% (with a spectral dependence) in order to minimize the QME residuals; additional information is available at http://tyler.ssec.wisc.edu/~davet/aeriqme/readme.html.

- Implementation and analysis of an AERI/LBLRTM QME for the SHEBA data set. This work shows the differences between the radiosonde and microwave radiometer measurements of integrated column water vapor during SHEBA, their impact on the computed downwelling radiance, and comparisons to the AERI-ER observations; a poster presentation can be downloaded at http://tyler.ssec.wisc.edu/~davet/webfiles/sheba_qme.ppt,sheba_qme_handout.ppt.

- Creation of monthly and yearly averages and time series of downwelling radiance and cloud radiative forcing from the 1995-2000 SGP AERI and 1998-2000 NSA AERI-ER high spectral resolution observations. This is a first step in the effort to compare the AERI observations to climate model output to assess model performance in reproducing cloudiness and cloud radiative properties. Posters on this material are available at http://tyler.ssec.wisc.edu/~davet/webfiles/aeri9499.ppt and http://tyler.ssec.wisc.edu/~davet/webfiles/barrow9800.ppt.

5. Progress and accomplishments during last twelve months

a. WVIOP 2000 and AFWEX

WVIOP 2000 and AFWEX are upcoming IOPs that have the goal of improving and quantifying our ability to measure atmospheric water vapor. During the past year, planning and organization has taken place such that we expect to conduct two very successful experiments this year. The goals of the experiments are to bring closure on the absolute accuracy of the ARM integrated column water vapor measurements, and to quantify the accuracy of the ARM measurements in the upper troposphere. These goals involve, primarily, the performance of the ARM microwave radiometer and the ARM Raman lidar, respectively. The IOPs bring together the operational ARM measurements with a range of IOP instrumentation and measurement capability that will allow for assessment of these issues. Due to scheduling problems, we have been forced to conduct the experiments in two different time periods: WVIOP 2000 from September 18 to October 18 and AFWEX from November 27 to December 15. A science plan and more logistical information is available at http://yard.arm.gov/~turner/afwex/.

b. Self-broadened Water Vapor Continuum Analysis

The existing AERI/LBLRTM QME analysis has shown that the current modeling of the clear sky atmosphere and its absorption is accurate to within ~2 W/m^2 in reproducing the observed downwelling flux. The QME data, however, also shows distinctive trends with increasing water vapor amounts. This analysis is based on a set of downwelling calculations with perturbations to the input water vapor profiles and continuum coefficients to determine if the behavior of the observed AERI/LBLRTM QME radiances residuals can be simulated. The emphasis is on the ~800 to ~1100 cm^{-1} region, where the simulated downwelling radiances are highly sensitive to the self-broadened water vapor continuum coefficients, C_s^0, and to precipitable water vapor. The simulations are LBLRTM calculations performed using the standard Tropical temperature profile and with varying relative humidity profiles giving precipitable water vapor values of 1, 2, 3, 4, 5, and 6 cm. The QME dataset is that from the ARM Southern Great Plains site from 1994 through 1997, which includes clear sky downwelling high spectral resolution radiance observations from the Atmospheric Emitted Radiance Interferometer at the site (AERI-01) and calculations performed with the line-by-line algorithm LBLRTM. The QME calculations use the CKDv2.3 water vapor continuum, which, for the 8-12μm region, includes the modifications due to the Kavieng, Papua New Guinea, observations, and input water vapor profiles specified by radiosonde profiles scaled to have the same precipitable water vapor as derived from coincident retrievals from the ARM Microwave Radiometer. (The simulations presented here use the CKDv2.4 continuum, which for the spectral regions considered here, can be considered identical to CKDv2.3, and CKDv2.1. Both the simulations and the QME calculations use the HITRAN 96 (JPL extended) spectral line database.) Also included is data from a representative case study from the ship-based Combined Sensor Program (CSP) in the Tropical Western Pacific (between Manus and Nauru) in 1996. Supporting figures and a detailed description of this analysis is given at http://tyler.ssec.wisc.edu/~davet/aeriqme/figures.html.

Preliminary analysis results are:

- If the QME differences near 5 cm of pwv and from ~850 to 1000 cm^{-1} are assumed to be due soley to fractional errors in C_s^0, the C_s^0 need to be adjusted by values no more than -5% to -10% in order to minimize the QME differences. Values derived from QME differences near 4 cm pwv are roughly 2 times smaller (-3% to -6%). This conclusion is based on treating the scatter in the QME differences near 4 and 5 cm as random error. If, however, the scatter is interpreted as a systematic effects such as aerosols and the adjustments are made to fit the most negative QME residuals for 4 and 5 cm, the C_s^0 need to be adjusted by values as large as -12% to -14%. These adjustments have a spectral nature as given in the supporting figures.

- If the QME differences near 5 cm of pwv and from ~850 to 1000 cm^{-1} are assumed to be due soley to fractional errors in the CMWR pwv values, the pwv inputs need to be adjusted by values ranging between -3% and -5% in order to minimize the QME differences. Values derived from QME differences near 4 cm pwv are roughly 2 times smaller (-1% to -3%). Note that fractional adjustments to the CMWR pwv values are not justified by the theoretical sensitivity of the 23 GHz BT's to pwv, as confirmed by comparisons to tower scaled Raman lidar profiles.

- AERI/LBLRTM QME differences for selected microwindows do go to zero as the precipitable water vapor goes to zero.

- As a function of increasing precipitable water vapor, AERI/LBLRTM QME differences behave more like fractional errors in C_s^0 and/or CMWR pwv than errors due to a pure offset in the input pwv.

- For the 990318 CSP case study (used in the Kavieng continuum adjustments), if the Vaisala radiosonde water vapor profile is adjusted by +5% to simulate the behavior of the packaging correction algorithm for similar sondes from TOGA COARE and used to drive the forward model with CKDv2.4, the resulting spectral residuals are consistent with the SGP QME residuals for similar water vapor amounts. If, however, the original (uncorrected for packaging corruption) Vaisala radiosonde water vapor profile is used to drive the forward model with CKDv2.4, the resulting spectral residuals are relatively small and do not follow the trend of the SGP AERI/LBLRTM QME dataset.

Our efforts are continuing to address the following issues:

- Look at behavior of QME differences for on-line water vapor spectral regions to distinguish between pwv and continuum dependencies.

- How does the spectral dependence of the possible C_s^0 adjustments shown here affect the interpretation of the spectral nature of the C_s^0 modifications derived from the Kavieng data?

- Incorporate more realistic temperature profiles into the simulations and investigate the temperature dependence of C_s^0.

- Incorporate an estimated error due to aerosol effects. Or, screen a subset of the data for which accurate aerosol optical depths are available.

3. An AERI-ER/LBLRTM QME for SHEBA

We have made comparisons of clear sky observed and calculated downwelling high spectra resolution radiances from the year-long SHEBA experiment. These and expected similar comparisons from the ARM NSA site in Barrow, Alaska, are useful for assessing the accuracy of clear sky forward model issues, particularly the far-infrared air-broadened water vapor continuum and the temperature dependence of the 8-12 mm self-broadened water vapor continuum, as well for assessing the accuracy of measured atmospheric temperature and water vapor profiles. This work is an extension of the original AERI/LBLRTM QME, which has been on-going at the SGP site since 1994, and of an analysis of several clear-sky SHEBA case-studies consisting of AERI-ER measurements and co-located radiosondes, which led to recent changes in the CKD representation of the far-infrared air-broadened water vapor continuum.

The supporting analysis draws upon a number of measurements collected during SHEBA including Vaisala RS-80 radiosonde profiles of temperature and water vapor, ARM microwave radiometer (CMWR) measurements of integrated column vapor and liquid water, AERI measurements of spectral downwelling radiance, and the ETL DABUL Lidar cloud measurements. The calculations were performed with LBLRTM with the CKDv2.4 water vapor continuum. ETL Lidar cloud height data product, MWR liquid water, and AERI radiances were used to determine clear sky periods. Requiring clear skies for 5 minutes prior and 45 minutes after the 11:15 and 23:15 UTC radiosonde launches, and requiring all necessary data (sondes, CMWR, Lidar, AERI) limits the number of clear sky cases to 62. These occurred between December 1997 and May 1998, with integrated column water vapor values between 0.08 and 0.5 cm, and near surface air temperatures between -40C and -10C. The CMWR integrated column water vapor values were averaged using data collected around the sonde launch times (5 minutes prior to 45 minutes after launch). For the dry, clear sky time periods, we find the radiosonde values to be roughly 30% dryer than the CMWR values.

For each of the 62 clear sky cases, downwelling radiative transfer calculations were performed and compared to the corresponding AERI observations. The calculations were performed using input water vapor profiles from the original radiosonde relative humidity profiles and with the sonde profiles scaled (independent of altitude) to have integrated column values equal to that of the CMWR. The mean residuals throughout the 8-12 μm window are on the order of +1 mW/(m^2 sr cm^{-1}) and show very little dependence on the input water vapor amount. Contamination by persistent aerosols, very large water vapor errors (i.e., +100% or +1mm), and/or unexplained AERI calibration errors are needed to explain these differences. The residuals in the 400-600 cm^{-1} region are more dependent on the input water vapor profile for these low water amounts, and the differences between the CMWR and radiosonde measurements are apparent in this spectral region. The mean residual due to the CMWR calculations are slightly negative (-2 mW/(m^2 sr cm^{-1}) on average), whereas those due to the sonde pwv are slightly positive (+1 mW/(m^2 sr cm^{-1}) on average). The standard deviation of the ensemble residuals for the CMWR scaled sonde calculations is roughly 2 times greater than those for the original sonde calculations. *Using AERI as a stable reference and the calculations as a transfer, this suggests that the CMWR pwv measurements during SHEBA exhibit greater variability (with respect to AERI) than the sonde measurements*. That is, the sonde-based calculations are better correlated with the AERI measurements than are the CMWR-based calculations. Other features apparent in the mean spectral residuals are due to inaccurate ozone amounts, temperature profile errors, and water vapor spectral line parameters.

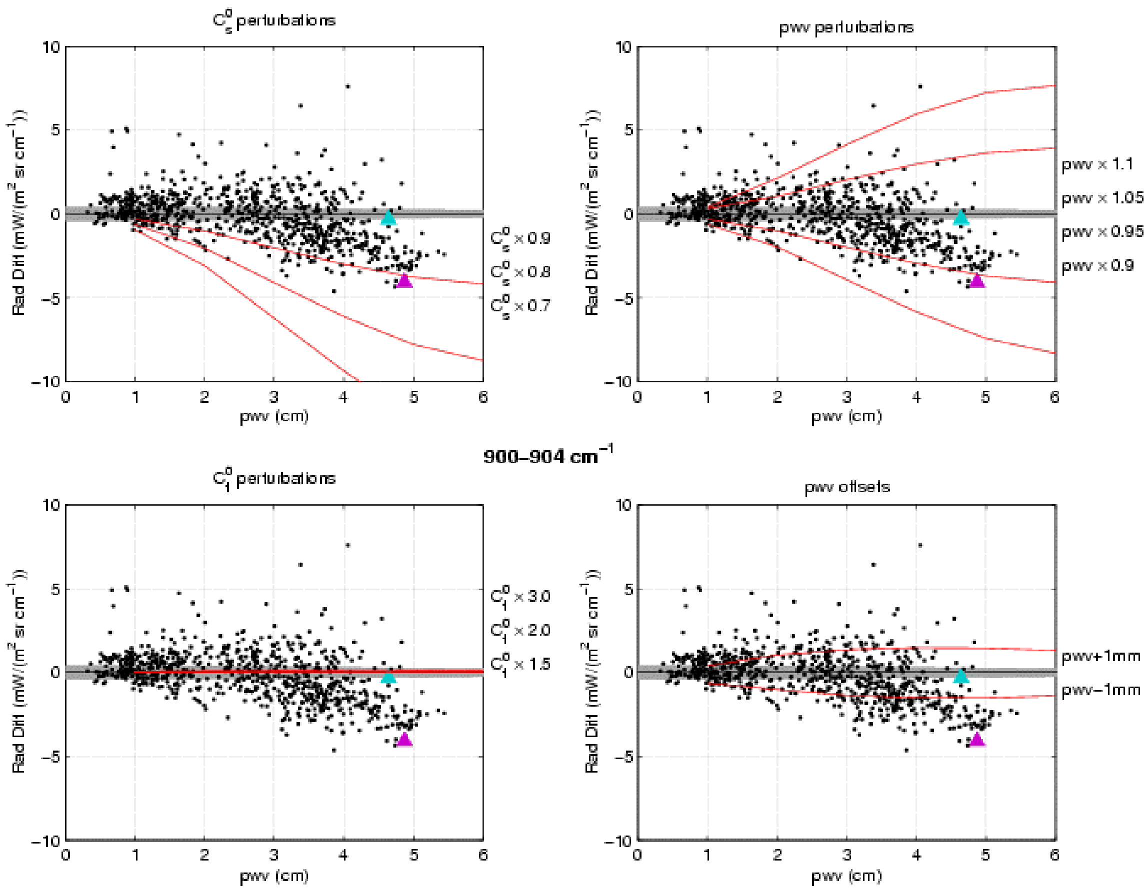
Future work for the SHEBA comparisons includes investigation of the cause of the 8-12μm radiance residuals and the CMWR variability, and using the SHEBA tethersonde profiles as inputs to the calculations. We also plan to extend these comparisons to the NSA site, with the focus on time periods where multiple microwave water vapor measurements (CMWR, ETL, MIR) and radiosondes are available.

4. Long-Term Averages of AERI Radiances and Cloud Radiative Forcing

The ARM Program has been making highly accurate measurements of the downwelling spectral radiance roughly every 8 minutes (neglecting infrequent instrument down times) with AERI systems at the SGP Central Facility CART site since July 1995 (since April 1994, including the original prototype AERI), at the SGP Boundary Facilities since December 1998, at the NSA site since February 1998, and at the TWP site since November 1998. A recent focus of our research has been to use this data to make meaningful comparisons to climate model output in order to assess the models' ability to produce clouds and cloud radiation. To this end, we have produced yearly and monthly summaries of the AERI radiances and derived cloud radiative forcing and radiance statistics. A few sample histograms showing the radiance distributions for different spectral averages are shown (below). Future research involves collaboration with climate/mesoscale modelers to obtain the required model output to a) perform downwelling radiance calculations (clear and cloudy sky) which can be compared to the AERI distributions, and/or b) manipulate (spectrally average, conversion to flux,…) the AERI radiances in order to compare to existing model output.

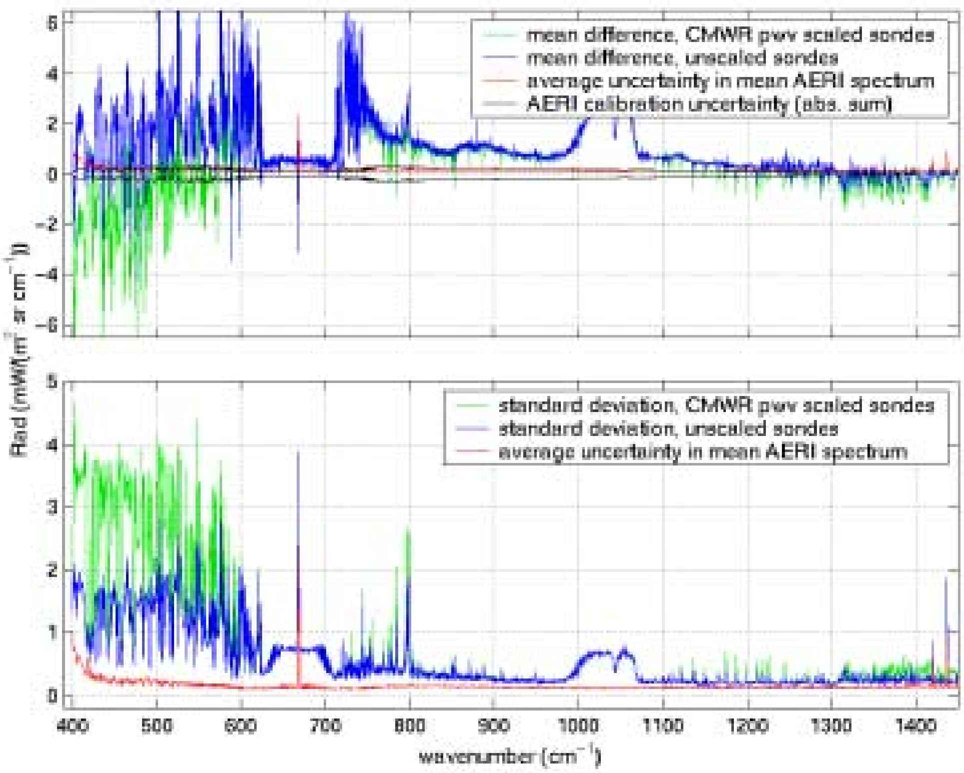
6. **Figures:**

SGP AERI/LBLRTM QME Residual Analysis



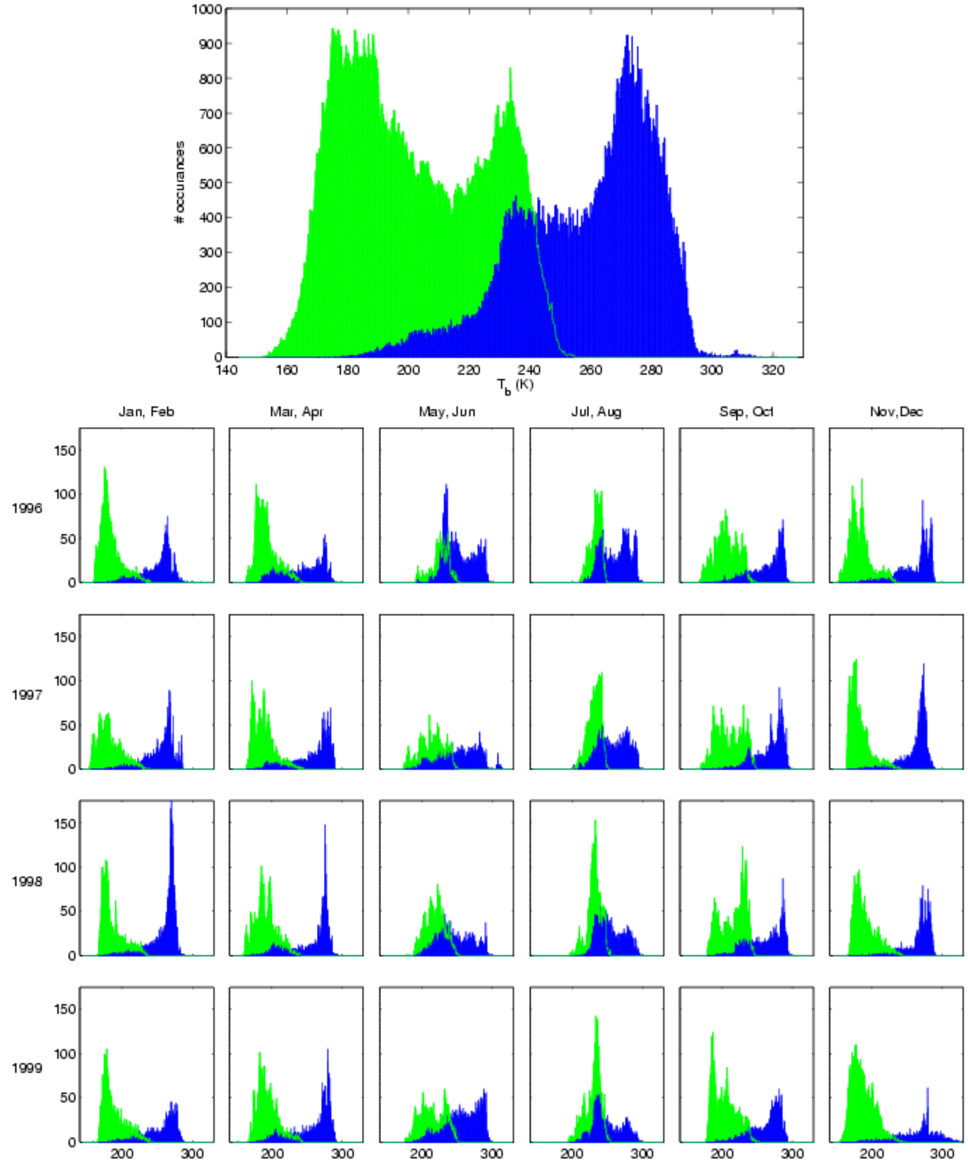
The 1994-1997 SGP site AERI/LBLRTM QME radiance residuals (black dots) plotted versus the CMWR integrated column water vapor values for the 900-904 cm^{-1} microwindow, along with contour lines showing simulated QME differences for perturbations to a) the self-broadened (Cs0) and b) air-broadened (Cf0) water vapor continuum coefficients used in the LBLRTM calculations, and to the precipitable water vapor (pwv) used in the calculations using c) pwv fractional changes, and d) pwv constant offsets. The observed QME differences can be minimized with a ~5%-10% decrease in the Cs0 coefficients or a ~3%-5% decrease in the input pwv, or some intermediate combination of both.

SHEBA AERI-ER/LBLRTM Radiance Residuals



Mean and standard deviation of spectral radiance residuals from the SHEBA AERI-ER/LBLRTM QME, consisting of 62 clear sky cases occurring between December 1997 and May 1998 with precipitable water vapor values ranging from 0.08 and 0.5 cm, and near surface air temperatures ranging from –40 and –10 C. The residuals are shown for LBLRTM calculations performed using the original Vaisala radiosonde profiles (blue) and for the CMWR scaled sondes (green), along with random and absolute estimates of the AERI observations. The difference in the mean residuals in the highly absorbing far-infrared region is due to the ~30% difference in the sonde and MWR pwv values (MWR 30% wetter than sondes). The standard deviation of the ensemble residuals (bottom panel) suggests that the CMWR pwv measurements during SHEBA exhibit greater variability (with respect to AERI) than the sonde measurements.

1996-1999 SGP AERI Window Region (985-900 cm^{-1})
Brightness Temperature Distributions



Yearly (top panel) and monthly (bottom panels) distributions of observed AERI brightness temperatures for the 985-990 cm^{-1} spectral region, which is a transparent channel with high sensitivity to integrated column water vapor and clouds, for clear (green) and cloudy (blue) scenes.

7. List all *refereed* publications either submitted or published during the *current* grant FY that acknowledge DOE ARM support. Two copies of all submitted papers should accompany the progress report. (Two reprints of all published papers should be submitted to the ARM Science Director when reprints are received. If this wasn't done at the time please include reprints with the progress report.*)

NONE

8. List all published (either paper or web-based) extended abstracts in the current FY that acknowledge DOE ARM support. Two copies of each should accompany the progress report*.

- Knuteson, R. O., F. A. Best, W. F. Feltz, R. K. Garcia, H. B. Howell, H. E. Revercomb, D. C. Tobin, and V. P. Walden, *UW High Spectral Resolution Emission Observations for Climate and Weather Research: Part II Groundbased AERI*, 10th Conference on Atmospheric Radiation, American Meteorological Society, Madison, WI, June 28 –July 2, 1999.

- Tobin, D. C., H. E. Revercomb, R. O. Knuteson, W. F. Feltz, and F. J. Murcray, *Weak Water Vapor Spectral Lines in the 8-12μm Atmospheric Window*, 10th Conference on Atmospheric Radiation, American Meteorological Society, Madison, WI, June 28 –July 2, 1999.

- Tobin, D. C., R.O. Knuteson, and H. E. Revercomb, Observed and Calculated Downwelling Longwave Spectral Radiances at the SHEBA Ice Station: prelude to an Arctic AERI/LBLRTM QME, Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 13-17, 2000, San Antonio, TX.

- Knuteson, R. O., F. A. Best, R. G. Dedecker, D. H. Deslover, T. P. Dirkx, W. F. Feltz, R. Garcia, H. B. Howell, H. E. Revercomb, and D.C. Tobin, AERIs for ARM: Accuracy and Applications, *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, March 13-17, 2000, San Antonio, TX.

- Clough, S. A., P. D. Brown, E. J. Mlawer, T. R.Shippert, D. D. Turner, D. C. Tobin, H. E. Revercomb, R.O. Knuteson, and R. G. Ellingson, A Longwave Broadband QME Based on ARM Pyrgeometer and AERI Measurements, *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, March 13-17, 2000, San Antonio, TX.

- Revercomb, H. E., D. C. Tobin, R. O. Knuteson, W. F. Feltz, and D. D. Turner, ARM-FIRE Water Vapor Experiment (AFWEX 2000): Background and Plans, *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, March 13-17, 2000, San Antonio, TX.

- Tobin, D., S. Ackermanm F. Best, R. Dedecker, D. Deslover, W. Feltz, R. Garcia, B. Howell, A. Huang, R. Knuteson, H. Revercomb, C. Sisko, P. van Delst, V. Walden, and H. Woolf, Remote Sensing and Energy Budget Applications of High Spectral Resolution Infrared Radiance Measurements in the Arctic, International Radiation Symposium, IRS 2000, St. Petersburg, Russia, July 24-29, 2000.

- Revercomb, H. E., F. A. Best, R. O. Knuteson, W. F. Feltz, D. C. Tobin, V. P. Walden, D. H. Deslover, R. G. Dedecker, R. K. Garcia, and H. B. Howell, Atmospheric Emitted Radiance Interferometer (AERI): ARM High Spectral Resolution Clear and Cloudy Observations, IGARSS 2000, Honolulu, Hawaii, July 24-28, 2000.

- Turner, D. D., H. Linne, J. Boesenberg, S. Lehmann, K. Ertel, J.E.M. Goldsmith, and T. P. Tooman, Simultaneous ground-based remote sensing of water vapor by differential absorption and Raman lidars. IEEE 2000 International Geoscience and Remote Sensing Symposium (IGARSS 2000), Honolulu, HI 2000. PNNL-SA-33128.

- Turner, D. D., R. A. Ferrare, L. A. Heilman, and T. P. Tooman, A two-year climatology of water vapor and aerosols in the lower troposphere measured by Raman lidar. Preprints of the 20th International Laser Radar Conference, Vichy, France, 2000.

9. Please update us on the status of submitted referred publications from the previous FY progress report.

Accepted to JGR:

Tobin, D. C., F. A. Best, S. A. Clough, R. G. Dedecker, R. G. Ellingson, R. K. Garcia, H. B. Howell, R. O. Knuteson, E.J. Mlawer, H. E. Revercomb, J. J. Short, P. F. W. van Delst, and V. P. Walden, 1999: Downwelling Spectral Radiance Observations at the SHEBA Ice Station: Water Vapor Continuum Measurements from 17-26μm, *JGR*, **104**, 2081-2092.